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Effect of available solar irradiance on vertical farming in semi-open urban places

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ABSTRACT

Building a vertical farm in unused residential and commercial spaces is a challenge. It is particularly hard to decide upon a space where varying degrees of lighting conditions may prevail at different times of a day. This experiment was focused on how innovative micro-irrigation technology could be coupled with vertical farms. In this regard, three storied racks were designed to accommodate multiple one-feet-square tubs large enough to hold five Indian spinach (BARI Puishak- 2) plants at a time. Sandy loam soil was used for farming along with recommended doses of fertilizers. Different lighting conditions (2- 145 W/m^2 average solar irradiance) were employed on the fifth floor of an urban building. Drip emitters were coupled in the system for irrigation. The management allowed deficit was kept to a maximum of 50% of the readily available moisture below the field capacity. The results suggested that drip irrigation systems provide higher water productivity (up to 31.82 kg/m^3) compared to the in-field conditions when BARI Puishak-2 is grown in vertical farming. Water productivity of spinach was improved by optimized set-up of a drip irrigation system. The study also concluded that vertical farming is only suitable for indoor places where plenty of direct sunlight or diffused sunlight (not below 70 W/m^2) is available. The economic analysis suggests that vertical farms under direct sunlight can be made profitable (BCR>1) in the long run.

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I. Introduction

Vertical farming is a technology of growing plants in a vertical orientation. It is the practice of producing food and medicine in vertically stacked layers, vertically inclined surfaces and/or integrated with other structures such as in a skyscraper, used warehouse or shipping container. The modern ideas of vertical farming use indoor farming techniques and controlled-environment agriculture (CEA) technology (Birkby, 2016). This type of agriculture is very well suited for urban culture (Beacham et al.

2019) where multi-storied buildings are used for agriculture. It is particularly appropriate for the cultivation of horticultural crops such as leafy vegetables (Al-Kodmany, 2018). The simple concept of vertical farming uses less land, less water and promotes great yield. Vertical farming consumes 70 percent less water compared to conventional farming methods (Saravanan et al., 2018).

The UN predicts, by 2050, around 70 percent of the world population is expected to live in urban areas, and the growing population will lead to increasing demand for food (UNDESA, 2015). As increasing urbanization is seen as unavoidable (UNDESA, 2004), new approaches should contribute to delivering fresh, local food for cities (Brock, 2008). Urban agriculture is currently considered one of the solutions to climate change adaptation as it can play a significant role in greening the city and improving the urban climate while stimulating the productive reuse of urban organic waste and reducing the urban energy footprint. In addition, agricultural land may be lost through the expansion of urban areas and infrastructure development (Brock, 2008), potentially leading to shortages of farmland (Corvalan et al., 2005). Besides the limitation in productive land, food crops are now competing for land, water, and other resources in many parts of the world as other types of land use emerge (FAO, 2012). This scale of change indicates that the planet is running short of farmland to feed a growing number of people (UNDESA, 2015).

The efficient use of vertical farming may play a significant role in preparing for such a challenge. Vertical farming needs to be taken care of properly with an adequate amount of water, lighting and temperature. Micro irrigation is one such technology that can be used to apply water into the crop root zone of vertical farms using micro emitters. Among them, drip technology can offer further water saving in vertical farms. Despite many efforts, very little is known about the management of micro-irrigation in multi-storied farming particularly in semi-open urban spaces. This study reports the results of a series of experimental studies carried out to investigate how micro-irrigation could be incorporated in vertical farming and, also aimed to evaluate the water use efficiency and other aspects of vertical farming in semi-open urban places.

Vertical farming can grow crops with 70 to 95% less water than the required amount for normal cultivation (Healy and Rosenberg, 2013; Thomaier et al., 2015). However, innovative water application methods are required to achieve this goal. Although the micro-irrigation system has high watering efficiency, very little is known about the management of this technique in multi-storied farming in semi-open urban spaces. This manuscript aims to investigate this area of concern by working with a micro-irrigation model in a vertically developed farming structure suitable for urban platforms.

II. Materials and Methods

The vertical farm was built in a semi-open place at the multi-storied BS building corridor of level 5 in Bangabandhu Sheikh Mujibur Rahman Agricultural University. The experiments were carried out during the summer months of March/2020 – August/2020. A mixture of sandy loam soil and cow dung manure was used as a growing medium on the tubs. During soil preparation, the soil was fertilized with 30% well-decomposed cow dung, 1kg of Muriate of Potash (MoP) and Diammonium Phosphate (DAP). After adding some water, it was kept for 15 days for decomposition. Urea fertilizers were applied to the standing crops with irrigation water through drip fertigation system. After obtaining the required tilth, Indian spinach (*Basella alba*) viz. BARI Puishak-2 seeds were sown into the square flower tubs on the shelves in a rack (Figure 01) on the 25th March 2020. Light drip irrigation was provided in the evening after sowing of seeds. Three racks were constructed with Aluminum each having three shelves for planting crops. The dimensions of each shelf were 1.524 m × 0.457 m (L×W). Each rack consisted of three shelves, and each shelf contained three tubs totaling nine tubs in a rack. The soil volume in each tub was 0.265 m ×0.265 m× 0.21 m, where 5 plants at a spacing of 0.05m×0.05m were sown. The distance between two tubs was kept 0.152 m, and free working space between two shelves was 0.686 m.

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(a) (b) (c)

Figure 01. Three micro-irrigation models for three different vertical farming systems under a) direct sunlight (L1); b) defused sunlight (L2), and c) artificial light (L3).

Solar irradiation treatments

The plants in this experiment were exposed to different lighting conditions in different semi-open urban spaces. Three different lighting conditions were employed in the experimentations. These are:

L1 = plenty of direct sunlight;
L2 = no direct sunlight but plenty of diffused sunlight, and
L3 = no sunlight but artificial lights were provided to mimic indoor conditions.

To meet the need for artificial lighting, LEDs (Light Emitting Diodes) sources have been suggested in the literature (Despommier, 2010; Germer et al., 2011; Möller, 2013). LEDs that have a longer life and lower price are decent choices (Stryjewski et al., 2001; Yorio et al., 2001) in this regard. To establish the treatments, three separate drip irrigation systems (Figure 01-a, b and c) were set up to supply the water into the tubs. Each drip system consisted of one mainline (19 mm diameter) hoisting three laterals (12.7 mm diameter) in all the racks. Laterals were spaced 0.76 m apart, and emitters were installed at a distance of 0.45 m from each other. A 120 mesh (130 micron) disk filter was used to filter the water before its delivery to every system. A water tank was placed on the top of each rack which was the main water source for the system. The light exposure intensity (W/m^2) was measured continuously at 10.00 am, 1.00 pm and 5.00 pm by a solari-meter (Figure 02) at one day's interval.

Figure 02. Measurement of solar irradiation by solar power meter

Drip irrigation efficiency measurement parameters

The discharge rate of an emitter was obtained by capturing the emitted water using catch cans of known weights (500 mL) placed under the laterals for at least 5 minutes (ISO, 2004). The equivalent volume of the collected water was then translated to obtain the hourly flow rate of an emitter reported as liters per hour (L/hr.). A stopwatch was used to measure the discharge times. The efficiency of drip irrigation systems was found out based on the recognized performance indices from ASABE and ISO 9261 guidelines for pressurized irrigation systems.

Manufacturer's coefficient of variation (CV_m)

The emitter manufacturer's coefficient (CV_m) of variation was calculated using the following formula (ASAE, 1996):

$$CV_m = \frac{S_d}{\underline{q}} \tag{1}$$

Where CV_m is manufacturer's coefficient of variation of emitter flow,
S_d is standard deviation of emitter flowrates at reference pressure head (L/hr.),
$\underline{q}$ is mean emitters flowrate in the sample at that reference pressure head (L/hr.).

Emission uniformity (EU)

The following equation is recommended by ASABE standards (ASABE, 2014) to estimate the design emission uniformity (EU) in terms of CVm and minimum emitter discharge (q_{min}).

$$EU=100 \times [1.0 - \frac{CV_m}{\sqrt{n}}] \times \frac{q_{min}}{\underline{q}} \tag{2}$$

Statistical uniformity (Us)

The statistical uniformity of emitters along the laterals was found out by using the following uniformity formula:

$$U_s = 100 \times (1 - CV_m) \tag{3}$$

Lower quarter distribution uniformity

The lower quarter distribution uniformity determines how uniformly irrigation water can be distributed through a drip irrigation system into the field. It uses the average of lower quartile discharge ($q_{1/4}$) to calculate the index as follows

$$DU_{1/4}=100 \times (\frac{q_{\frac{1}{4}}}{\underline{q}}) \tag{4}$$

Water use and productivity calculation:

The amount of irrigation water (m) to be given during one set of irrigation events was determined based on the moisture depletion status of the soil in the tub. The maximum management allowed deficit (MAD) was set to be 50% of the readily available moisture determined using a volumetric soil moisture reader. Total seasonal crop water use (SCWU) was calculated as the sum of total irrigation water applied (IW) and soil water contribution (SWC) between plantation and final harvest, expressed by the following equation modified from Sarker et al. (2019).

$$SCWU = IW \pm SWC \tag{5}$$

The economical crop yields (CY) of Indian spinach (*Basella alba)* viz. BARI Puishak-2 was recorded (kg/m²) for each lighting treatment. Water productivity (WP) was calculated as the ratio of yield and total seasonal water use using the following equation.

$$WP\ (kg/m^3) = CY/SWCU \tag{6}$$

Crop management and data collection

After emergence of seedlings, various intercultural operations i.e., weeding, top dressing was accomplished for better growth and development of the Indian spinach seedlings. Drip irrigations were provided to the tubs once immediately after germination. When the seedlings were well established, the

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soil around the base of each seedling was pulverized. A few gap filling was done by healthy seedlings of the same stock where initial planted seedling failed to survive. In early stage leaf eating caterpillar attacked the plants and was controlled by spraying Limithion @ 2 ml/L of water. Grasshoppers were also noticed and were controlled by spraying insecticides (Cranshaw and Hammon, 2008). There was also an appearance of leaf spots which was controlled by Spraying Bavistin/Knowin at 2 g/liter of water at an interval of 10 days. Crop yield and yield contributing character data were collected randomly from all shelves of the respective tubs. One randomly selected sample plant was selected from each tub for data collection at 18, 24, 33 and 44 days after seed sowing (DAS). Plant height, Number of leaves per plant, Leaf area per plant (cm^2), Number of branches per plant, Gross yield (g $Shelf^{-1}$), Total yield (gm-$Rack^{-1}$) data were collected from all the shelves in a rack for all the lighting conditions.

Economic analysis

The cost of production was analyzed to find out the most economical vertical farming in semi-open urban places. All input cost included the cost for rack preparation and interests in running capital in computing the cost of production. The market price of Indian spinach was considered for estimating the cost and return. The benefit cost ratio (BCR) was calculated as follows:

$$\text{Benefit cost ratio (BCR)} = \frac{Gross\ return\ per\ square\ meter\ of\ floor\ space\ (Tk.)}{Total\ cost\ of\ production\ per\ square\ meter\ of\ floor\ space\ (Tk.)}$$

III. Results and Discussion

Variation in solar irradiation

Harvesting solar irradiation in an urban residential or commercial complex is often a tough endeavor. It is however important to quantify the amount which can be safely harvested from such scenarios because variation in solar radiation intensity in urban spaces could affect the growth and yield of plants even if supplemented by artificial lights (Arora et al., 2017). Based on the three different lighting conditions (L1, L2 and L3) that can prevail in any building, the measurement of irradiance was carried out on each shelf of the racks. The monthly variation has been shown in Figure 03 for three different lighting conditions (L1, L2 and L3). The highest average solar irradiation (145.73 Wm^{-2}) was received from direct sunlight during June and the lowest (86.92 Wm^{-2}) in April (Figure 03). Direct sunlight also varied within the months which can be read from the error bars. In case of diffused sunlight, the lowest solar irradiation (74.52 Wm^{-2}) also occurred during April and the highest (97.92 Wm^{-2}) in June. Among the three different lighting conditions, LED lights emitted the lowest lighting condition (Figure 03) which was below 2 Wm^{-2}.

Yield contributing characters at different lighting conditions and days after sowing

The plant height of Indian spinach was significantly influenced by three different lighting conditions. Data collected at every 18, 24, 33 and 44 days after sowing (DAS) have been shown in Table 01. The result revealed that plants in the L1 and L2 lighting conditions were taller than those under artificial light treatment. The tallest plant height (19.07 cm) was observed for L1 conditions (Table 01) and the lowest plant height (17.03 cm) was observed from artificial lights (L3) at 44 DAS. After that age, the maximum tip of the Indian spinach in L3 was dried out and henceforth could not survive. The artificial lighting intensity below (2 Wm^{-2}) that was usually obtained using bright LED lights appeared to be insufficient for crop growth. This research indicates that in order to practice urban agriculture, lighting conditions in residential or office settings must be set to at least 70-80 Wm^{-2}. Varying degrees of such requirements have been depicted in previous researches of Joshi-Paneri et al. (2020) and Nguyen et al. (2019). This is understandably a site-specific issue and should be investigated in further detail.

A non-significant variation in number of leaves per plant was recorded between L1 and L2 conditions (Table 01). On the other hand, the artificial lights (L3) yielded a significantly lower number of leaves at all stages during the growth period. At 44 DAS, the maximum number of leaves per plant (9.0) was obtained from L1 whereas the minimum (2.57 per plant) from L3. While all the plants in L1 and L2 grew over time, the number of leaves in L3 conditions began to go down after 33 DAS (Table 01). These findings may be related to the chlorophyll content of the leaves. In artificial lights at 44 DAS due to the low light condition, the green color disappeared from the leaves, and yellow to orange became visible. Similar experiences for indoor plants with artificial lights were reported by Nguyen et al. (2019). The leaf area measured at different growth stages revealed that statistically significant difference exists amongst the treatments. The maximum leaf area (89.62 cm^2) was recorded from the direct L1 condition, and the minimum (5.78 cm^2) was recorded from L3. Campillo et al. (2012) described that the productivity of a crop depends on the ability of plant cover to intercept the incident radiation, which is a function of the leaf area available. Because of the lower intensity of lights indoor, treatment L3 could not produce leaves large enough to convert the energy captured by the plant.

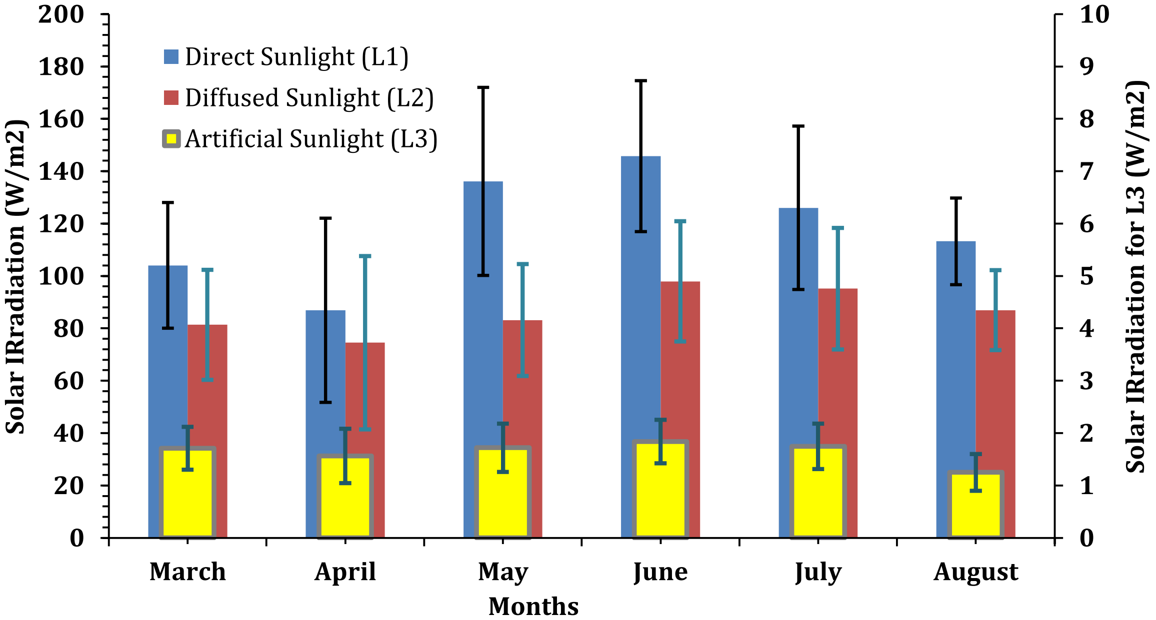

Figure 03. Intensity of solar irradiation during the growing months for plants grown under different lighting treatments

Table 01. Yield contributing characters at different days after sowing

Parameters	Lighting treatments	Days After Sowing			
		18 DAS	24 DAS	33 DAS	44 DAS
Plant Height	L1	8.93 a	11.40 a	14.43 a	19.07 a
	L2	7.08 a	9.47 a	14.03 a	17.03 a
	L3	3.73 b	5.30 b	8.33 b	5.90 b
Number of leaves/Plant	L1	4.67 a	7.00 a	9.33 a	11.00 a
	L2	4.33 a	6.33 a	8.33 a	9.00 a
	L3	2.67 b	4.33 b	5.00 b	2.67 b
Leaf area	L1	18.48 a	43.21 a	89.62 a	76.61 a
	L2	16.88 a	35.97 a	73.88 b	64.18 b
	L3	5.78 b	18.06 b	61.73 c	42.95 c

*Values with similar letters do not vary significantly within their own category

Drip Irrigation systems performance measurement parameters

The uniformity indices of three drip irrigation systems were estimated for all the lighting conditions (Table 02). The results indicated that the manufacturer's coefficient of variation (CV_m) was marginal (7%) for L1, average (6%) for L2, and marginal for L3 according to the classifications of ASABE (2006). The Distribution Uniformity for each lighting treatment was in "very good category" (ASABE 2006) for all systems. The Christiansen's coefficient of uniformity (CUc) was in the range of 80-90% which is "good category" according to ASABE standards EP458 (ASABE 2006). The statistical uniformity (Us) of all the systems was obtained within 90-94% which indicates "very good category" based on ASABE (2006) throughout all the systems. The Emission uniformity (EU) of drip irrigation systems was found between 80-90% at all lighting treatments, hence, according to ASABE (2006), this drip system can be titled as "good".

Table 02. Hydraulic performances indices of the drip emitters used in growth racks

Parameters	Direct sunlight (L1)	Diffused sunlight (L2)	Artificial lights (L3)
CVm	0.07	0.06	0.07
DU (%)	91.88	93.35	92.47
CUc (%)	87.54	87.19	87.19
Us (%)	93.32	93.95	93.14
EU (%)	87.97	89.45	85.48

Yield and water productivity

Table 03 shows a summary of yield, water use and water productivity of Indian spinach under three different lighting treatments. The highest yield was 11.85 kg $Rack^{-1}$ for L1 followed by 8.39 kg $Rack^{-1}$ and 1.39 kg $Rack^{-1}$, for L2 and L3 treatment, respectively. Water productivity (WP) was estimated to describe the relationship between the yield of spinach and the amount of water consumed. Seasonal consumptive water use (SCWU) and water productivity (WP) varied among the treatments due to different moisture depletion scenarios. The management allowed deficit was set to be a maximum of 50%. Hence, frequent irrigation was applied through drip irrigation system. In this experiment, the highest SCWU was reported for treatment L1 with 180 mm water required to produce a total of 11.85 kg of spinach from a rack (Table 03). This means urban residential and office indoors or roofs could be used to produce potentially 5.67 kg of spinach using per square meter of floor space.

Table 03. Yield, water use and water productivity of BARI Puishak 2 under drip irrigation

Treatment	Crop yield (kg/Rack)	Crop yield (kg/m^2)	SCWU (m)	WP (kg/m^3)
L1	11.85	5.67 *a*	0.18	31.82
L2	8.39	4.02 *b*	0.15	27.35
L3	1.39	0.67 *c*	0.06	11.70

Using the racks demonstrated in this study, only in typical verandas, 2.1 m^2 areas could be easily spared for urban farming. Considering the growth of spinach and harvesting almost every week, this amount is ample to meet the leafy vegetable needs of a small family all year-round. One important aspect of such farming is that water productivity is very high. For instance, in case of L1, the WP was found to be 31.82 kg/m^3 which is higher than most document WP in field conditions that ranges from 20-25% (Sarker, 2019). In case of L2 conditions, water productivity was also very impressive (27.35 kg/m^3). On the other hand, artificial lighting condition yielded the lowest (1.55 kg/m^3) water productivity (Table 03) and is not recommended for urban farming. Achieving such higher water productivity is not possible in the field conditions due to higher evaporative demand of the open air. Using drip irrigation in urban spaces is therefore an important tool to utilize fresh water resources efficiently for vertical farming where plenty of direct or diffused sunlight is available.

Economic analysis

All the material and non-material input costs like rack preparation, seed cost, manure and fertilizers, irrigation and manpower required for all the operation, and miscellaneous cost were considered for calculating the total cost of production from sowing of seed to harvesting of Indian spinach. These items were recorded for unit rack used for vertical farming (Table 04). The cost (Table 04) would vary if larger or smaller units are built in residential or office settings. The cost of this particular setting could also be lowered if the mainframe of the shelves was built using materials other than iron angle bars. The price of Indian spinach was considered at market rate.

Gross return was calculated based on sale price of Indian spinach as shown in Table 05. The highest gross return (Tk. 948) was obtained from direct sunlight conditions and the lowest gross return (Tk. 111.2) was obtained from artificial light treatment. Net returns are also shown in Table 05. The highest net return (Tk. 248.81) was obtained from treatment direct sunlight (L1) and the lowest net return (Net loss Tk. -587.99) was obtained from artificial lights (L3). The defused light condition yielded a net return of (Tk -27.99). Among three different lighting treatments, variation of benefit cost ratio (BCR) was observed as shown in Table 05 considering an IRR of 5%. The highest benefit cost ratio (1.36) was obtained from direct sunlight (L1) condition, and the lowest (0.16) was obtained from artificial lights

(L3). From economic point of view, it was noticeable from the above results that vertical farming under direct sunlight was more profitable than the rest of the vertical farming arrangements.

Table 04. List of the materials and approximate cost for a DI system in vertical farming.

Description	Quantity	Unit price (Tk.)	Approximate cost (Tk.)
Construction of rack	1pc	10000	10,000
Water tank and filter	1pc	3350	3350
Tubs	9	190tk./pc	1710
Emitter	9 pcs	10 tk./pc	90
1.5-inch Main pipe	40ft	10 tk./ft.	400
½ inch sub main Pipe	20 ft.	7tk./ft.	140
1.5 " + ½" End Caps	1 pc + 3 pc	50tk./pc + 20tk./pc	110
1.5"×1.5"(T)Connectors	1 pc	100tk./pc	100
½"×1.5" (T) Connectors	3 pc	40tk./pc	120
Thread Tape	2 pc	20 tk./pc	40
Gate valve	1 pc	100 tk./ pc	100
Labor + others	LS	LS	1450
Total fixed cost (Tk.)			17,610

Table 05. Economic analysis of BARI Puishak 2 grown on vertical platform

Lighting Conditions	Economic analysis				
	Yield (Kg/Rack yr^{-1})	Cost of production ($Tk.yr^{-1}$)	Gross return ($Tk.Rack^{-1}yr^{-1}$)	Net return ($Tk.Rack^{-1}yr^{-1}$)	BCR
Direct sunlight (L1)	23.7	699	948	248.81	1.36
Defused sunlight (L2)	16.78	699	671.2	-27.99	0.96
Artificial light L3	2.78	699	111.2	-587.99	0.16

The results of this research bear important information for future endeavors regarding urban vertical farming. Using this information, residential and official floor spaces with direct or diffused sunlight can be converted into vertical farms. The potential yield scenario that has been discussed in previous sections suggests that vertical farming could potentially meet the demand of leafy vegetables of a family all year-round. If such scenarios are adopted in the building spaces, a huge quantity of vegetables could be produced from cities like Dhaka. More importantly, semi-open vertical farms could produce safe food for the urban population. The aesthetics of a green urban wall might also contribute to the mental wellbeing of the city dwellers. In addition to the aesthetic values, different household wastes such as non-edible parts of vegetables and fruits, after-meal wastes which are usually thrown away can be used as organic fertilizers in these kinds of vertical farms. Vertical farming may also alleviate poverty, generating additional income and creating employment.

IV. Conclusion

This study reports the results of three experiments carried out to understand how innovative micro-irrigation techniques could be coupled with vertical farms. In this regard, three storied racks were designed to accommodate one-feet-square tubs. Each tub was large enough to hold five spinach (BARI Puishak 2) plants at a time. Different lighting conditions (2- 145 W/m^2 average solar irradiance) were employed as in the indoors of residential or commercial floor space. Drip emitters were coupled in the system for irrigation. The management allowed deficit was kept to a maximum of 50% of the readily available moisture below the field capacity. The results suggested that drip irrigation systems provide higher water productivity (up to 31.82 kg/m^3) compared to the in-field conditions when BARI Puishak 2 is grown in vertical farming. Water productivity of Spinach was improved by optimized set-up of drip irrigation system. The study also concluded that vertical farming is only suitable for indoor places where plenty of direct sunlight or diffused sunlight (not below 70 W/m^2) is available. It is assumed that, if such scenarios are adopted in the unused building spaces, large quantities of safe and organic vegetables could be produced from cities like Dhaka.

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